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# EXTRACTION OF THE ACOUSTIC PART OF A TURBULENT BOUNDARY LAYER FROM WALL PRESSURE AND VIBRATION MEASUREMENTS

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## ABSTRACT

*The acoustic pressure in the nearfield of a wall in a flow can be decomposed in different components: a first part is related to the vortices resulting from the perturbation of the flow by the presence of the wall, a second part is due to the acoustic waves generated by the parietal pressure fluctuations diffracted by the wall, and a third part is potentially caused by any other incident acoustic wave. In many situations, one may be interested in the possibility of extracting experimentally the acoustic part of a parietal pressure. It can be achieved by directly measuring the parietal pressure using flush mounted microphones, and by applying post processing like denoising, wavenumber analysis, modal identification. However, the wall pressure fluctuation is generally largely dominated by the non acoustic part, which complicates the identification because of very low SNR. A second possibility is to identify the parietal pressure from the vibration of the wall itself using inverse methods. This approach offers the possibility to use the structure as a wavenumber filter, improving significantly the SNR. The aim of this paper is to compare two approaches based on direct and indirect measurements in the framework of an experiment in a wind tunnel. The direct approach uses several cleaning methods applied to the measured wall pressure fluctuation, and the indirect approach is based on the identification of the pressure from vibration measurements.*

## 1 INTRODUCTION

This study is based on a measurement campaign carried out in 2009 during the project IP²[1], granted by the French institute “institut carnot I@L”. One aim of this project was to compare the estimation of the turbulent pressure field induced by a flow on a flat structure from either pinhole microphone measurements, or indirectly from the vibration of a plate excited by the turbulent pressure field. The comparison of estimated pressure spectra led to the observation of differences of about 10 to 20dB between both approaches, the pinhole microphone measurement giving almost broadband spectra, and the identification from vibration measurements being much less energetic, but with several significantly emerging peaks. These peaks, that could not be found in the directly measured pressures, where identified as related to modal frequencies of the wind tunnel. A theoretical study of the indirect measurement method (known as FAT for Force Analysis Technique), showed a low pass filtering effect in the wavenumber domain [2], explaining the strong energetic difference between both approaches, the convective wavenumber being located above the cutoff wavenumber [3]. As shown in D. Lecoq's PhD thesis [4], the indirect estimation is not able to recover the high wavenumber components of the turbulent pressure field, but can be used to extract the low wavenumber components (which can be the acoustical part of the field in a given frequency range) that are hard to obtain from direct in-flow measurements. A direct consequence of this was that the comparison of both approaches was not possible.

The aim of this study is to present several approaches applied sequentially to try to recover the low wavenumber component from the pressure field measured directly in the flow. The results are then compared to the ouput of the indirect approach.

## 2 EXPERIMENTAL SETUP AND DIRECT PRESSURE MEASUREMENTS

Experiments are realized in a wind tunnel (50x50cm section, 6m length). The source of turbulence is a parallelepiped 10x10x6cm placed on the floor of the tunnel, and the mean air flow speed is 25 m/s. Pictures of the setup are given in Fig. 1.

Figure 1: Experimental setup: obstacle in the wind tunnel in front of the antenna (left), backside of the antenna (right).

The parietal pressure downstream of the cube is measured using a panel equipped with an antenna of 45 pinhole microphones (submillimetric holes), each microphone being calibrated beforehand using a specific procedure [1]. The antenna consists in 15x3 sensors, with a regular step of 25 mm; 15 sensors are along the direction perpendicular to the flow. The cube is moved at 9 positions in the tunnel, so as to cover a total measurement area of 700mm downstream from the cube. At each position, the pressures are recorded in the time domain during 50s with a sampling of 12.8kHz.

## 3 INDIRECT IDENTIFICATION OF THE PRESSURE FIELD USING FAT

A second measurement setup (see Fig. 2) is used for the indirect approach. A thin aluminium plate (480x800x0.6mm) is mounted in place of the wind tunnel's floor just downstream from the cube. The velocity of the plate is measured from the outside of the tunnel using an array of velocity sensors, sequentially moved along a plane using a 2D robot. The sensors are measuring the acoustic velocity in the very nearfield of the plate, (less than 1cm), and is thus assumed for continuity reasons equal to the velocity of the plate [5].

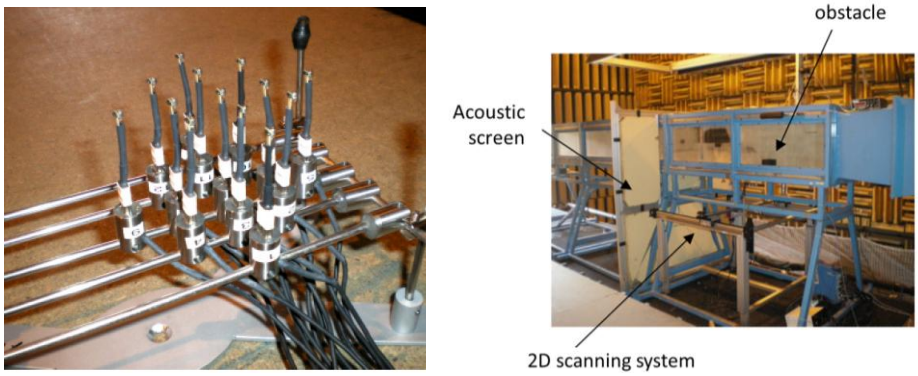


Figure 2: Experimental setup for indirect measurements: velocity sensors antenna (left), 2D scanning system below the wind tunnel (right).

The pressure exciting the plate is estimated for each position of the array using the Corrected Force Analysis [2] implemented in the time domain [6]. The incoherent nature of the vibration field of the plate complicates the use of referenced methods. The consequence is that the phase is lost between different positions (non-synchronous measurements): the output of the approach is thus simply an autopower map of the exciting pressure field.

## 4 COMPARISON BETWEEN DIRECT AND INDIRECT MEASUREMENTS OF THE PRESSURE FIELD

The pressure field downstream from the obstacle has been estimated directly using pinhole microphones and indirectly from the vibration of a thin plate. The average quadratic pressure spectra resulting from the two approaches are drawn in Fig. 3.

The CFAT is processed independently for each position; the standard k-space filter [7] cannot be applied. The low frequency part of the indirect estimation is thus not valid. A low frequency limit for the method without filtering is equal to 750Hz for the considered plate. Above 750 Hz, two major differences are observed between two approaches: first of all there is a level shift of around 20 to 25dB, and secondly the indirect estimation has some peaks, while the direct measurement is almost flat, slowly decreasing from about 5dB by octave.

These huge differences have found some explanation in previous works. Indeed, the CFAT has been found to return a low pass filtered (wavenumber domain) version of the excitation field [2]. For the setup studied in this work, the major part of the energy of the excitation is above the cut-off wavenumber [3,4], explaining that only a weak part of the excitation is recovered by the indirect method. The peaks that are observed on the indirect estimation correspond to transversal acoustic modes of the (0.5x0.5m) tunnel (cf. Fig. 3). These modes are completely hidden in the total pressure obtained by direct measurements. This highlights the potential of the indirect method to extract efficiently the low wavenumber where the "acoustical" part of the excitation is present.

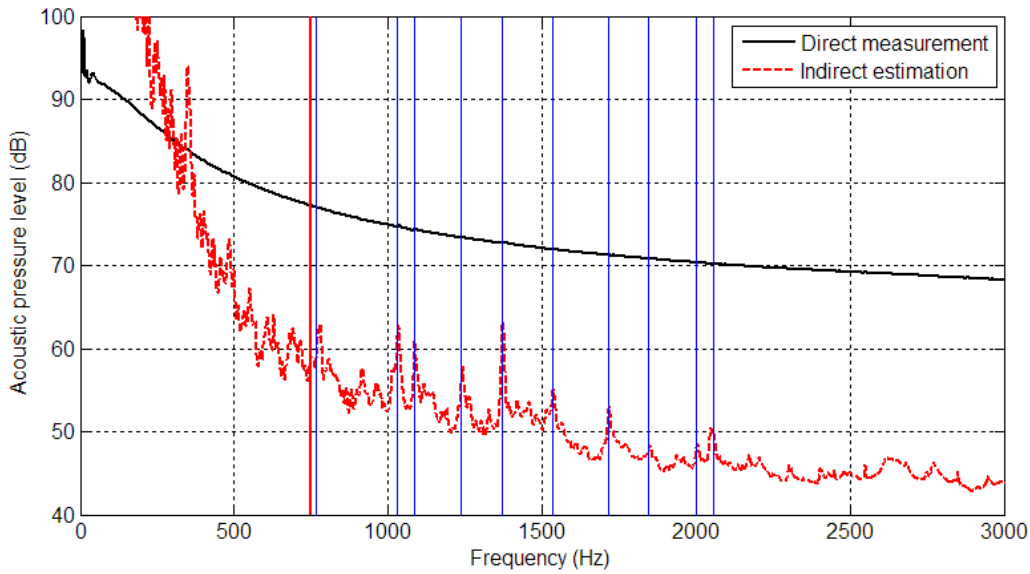


Figure 3: Comparison of average quadratic pressure spectra obtained from direct (black) and indirect (red) measurements. Low frequency limit of the indirect method (thick red vertical line), modes of the tunnel (thin blue vertical lines)

The following parts of this work are dedicated to a step by step "cleaning" of the direct measurements, using different strategies, aiming at the recovering of the acoustical part of the excitation field.

## 5 A STEP-BY-STEP CLEANING OF DIRECT PRESSURE MEASUREMENTS

The aim of this section is to propose a step-by-step analysis of the pressure measured in the flow, in order to recover the acoustic part of the field. The word "cleaning" used in the title of this section is used on purpose, because a large part of the acoustic field can be assumed to be carried by wavenumbers above the Shannon's limit (here the spatial sampling of the measurements is 25mm). The convective peak, especially, is above the Nyquist's wavenumber for frequencies above 500Hz. Thus, this high wavenumber part is inevitably aliased on the usefull wavenumber bandwidth, strongly contributing to a poor signal to noise ratio. Basically, interpreting Fig. 3 by considering that the signal is the part recovered by the indirect approach, the SNR can be roughly estimated at about -20dB.

### 5.1 Averaging microphones in the direction of the flow

The first cleaning stage is suggested by the shape of the array, being constituted of 3 lines of 15 microphones perpendicular to the flow. This shape does not allow one to directly apply modal identification techniques [8], because only 3 points are available in the direction of propagation of the modes of the wind tunnel. However, a first attempt of this work is to recover the peaks occurring at cut-on frequencies of the tunnel (cf indirect results in the previous section). At these frequencies, the axial wavenumber is about 0 (by definition), and the microphones in the same direction are all capturing the same information. This is the reason why these microphones are simply averaged (after the calibration stage). The effect of this averaging is shown in Fig. 4 (dashed red). Above 1kHz, the effect is to remove about 5dB, which is coherent with the theoretical division by a factor three of the energy of uncorrelated signals. It means simply that the 3 signals are almost fully incoherent. Some interferences are seen below 1kHz, either constructive or destructive, because of the spatial

structure of the turbulence, whose correlation lengths in the direction of the flow are of the same order or larger than the spatial sampling. A peak at about 340Hz becomes visible, corresponding to the first non-negative the cut-on frequency.

### 5.2 Denoising of the autospectra

A second step of the cleaning is an attempt to remove from each signal the part that is incoherent with all other signals. This operation is realized on the diagonal of the cross-spectral matrix (autospectra), which is the only part of the matrix whose expected value is affected by the uncorrelated noise. This step is quite usual in aeroacoustics: the classical approach is to simply zero the diagonal [9]. Another possibility, proposed by Finez et al. [10], is based on the assumption that all measurements are fully coherent. These approaches are leading to interesting results, but a major drawback is that the resulting cross-spectral matrix loses its property of positivity, guaranteeing that coherences remain below one.
We propose another approach here, based on alternate projections [11]:

*- set the diagonal to zero*
***loop*** *- compute eigenvalues,*
*- set negative eigenvalues to zero*
*- reinject measured cross-spectra*
*exit loop if (all eigenvalues are positive OR max. iteration number reached)*
***end of loop***

The result of the procedure is shown in Fig. 4 (solid blue line). Five more dBs are removed thanks to this procedure, on a wide frequency range above 250Hz. The peak at 340 Hz becomes more pronounced, and other peaks are barely visible between 1 and 1.5kHz, less than 1dB above the broadband contribution.

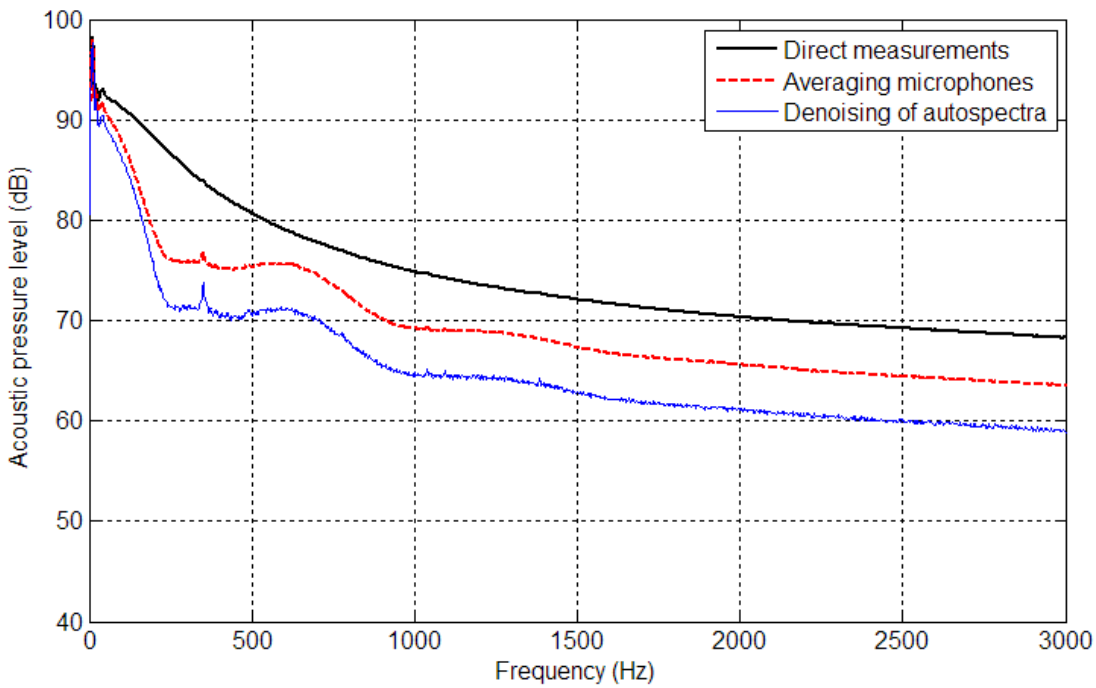


Figure 4: average quadratic pressure spectra. Solid Black: direct measurements. Dashed red: after step 1 (3 by 3 microphone averaging, cf. section 5.2). Solid blue: after step 1 and step 2 (autospectra denoising, cf. section 5.3)

### 5.3 Extraction of the signal by principal component analysis (PCA)

The third step of the cleaning process, after microphone averaging (cf. Section 5.1) and denoising (Section 5.2), is to apply a common denoising procedure: principal component analysis (PCA) [12,13]. This procedure aims at identifying in the cross-spectral matrix the contribution of a set of fully incoherent contributions. These contributions are represented by the eigenvalues and eigenvectors of the matrix. The difficulty is to separate the signal from the noise in all the eigenvalues. A basic strategy is to consider that the signal is carried by the most energetic ones; a hypothesis that can be hard to admit in a situation with a SNR equal to -20dB. However, it can be assumed that the signal is carried by very few components, while the noise is distributed on other ones. It means that the energy of the noise is distributed on a lot of eigenvalues, dividing the individual contribution of each noise component by the total number of components. Under this perspective, the contribution of each noise component can be roughly estimated as the total level divided by the number of eigenvalues. With 15 signals (after the three by three microphone averaging realized at step 1, reducing the number of channels from 45 to 15), the mean contribution of each noise component can be assessed as about -12dB of the overall level. Considering that step 1 and step 2 have already removed about 10dB of noise, and that the expected SNR on peaks is expected to be above -20dB (see Fig. 3), it is justified to simply consider that the signal corresponds to the most energetic eigenvalue. However, in other situation, a more sophisticated eigenvalues selection strategy might be implemented.

The contribution of the first eigenvalue to the average autospectra is presented in Fig. 5 (in blue). This cleaning operation removes about 8dB more on the broadband noise, and a bit less on peaks, comforting the hypothesis that at least a significant part of the signal is carried by the most energetic principal component, in our case.

### 5.4 Modal identification

A last operation consists in the application of a simplified modal identification approach. A full modal identification is not feasible in our case, because as it was said before we have too few information in the direction of propagation (only one, in fact, after the averaging operation realized in step 1), and the microphones are measuring the wall pressure fluctuation on one wall only of the wind tunnel. Considering that z is the flow / propagation direction, and that the array is in the plane xz (see Fig. 1), all sensors are placed at the same position in the y direction. The modal matrix thus is ill-conditioned even considering very few modes. A simplified approach is considered here, just by projecting measurements on a base of cosine functions over the dimension of the array:

$$p(x) = \sum_{n=0..N} a_n \cos(n\pi x/L) \qquad (1)$$

written in matrix form (SIMO and MIMO cases) :

$$p=\Phi a, \qquad S_{pp}=\Phi S_{aa}\Phi^H \qquad (2)$$

where $\Phi$ is the matrix of modes expressed in Eq. (1). It is clear that this approach is not able to really separate propagating modes, because several modes will contribute to each component. All modes with an index n on the x direction will contribute to $a_{0,}$ whatever the index in the y direction. However, this is the only possibility to proceed in our case, to make matrix $\Phi$ invertible. The modal projection matrix $\Psi=\Phi^{+}\Phi$ is finally defined as follows:

$$S_{aa} =\Phi^{+}S_{pp}\Phi^{+H}, \qquad S_{pp}'= \Psi S_{pp}\Psi^H \qquad (3)$$

This simplified modal identification has been implemented in our case for different values of N (maximum for index n, defining the truncation order of the modal basis). The best SNR

(assessed by the difference between peaks and broadband) is obtained for only 2 considered modes, i.e. the static component and the half cosine (indices n=0 and 1). The results of the identification are given in Fig. 5 (red). These results are quite spectacular because the modal identification removes about no energy on peaks, but the broadband noise in lowered of 6 to 10 more dBs, nicely increasing the relative contribution of the peaks.
It is noted that the ordering of the denoising steps has a significant effect on the result. In Fig. 6, the ordering used in the previous section is compared to an alternative order in which the modal identification is realized before the principal component analysis. It is clear that the former lead to a better SNR (difference of about 5dB). It means that the modal identification takes advantage of the denoising brought by PCA while the PCA is less efficient from the result of modal identification, probably because this operation has a correlation effect on the noise.

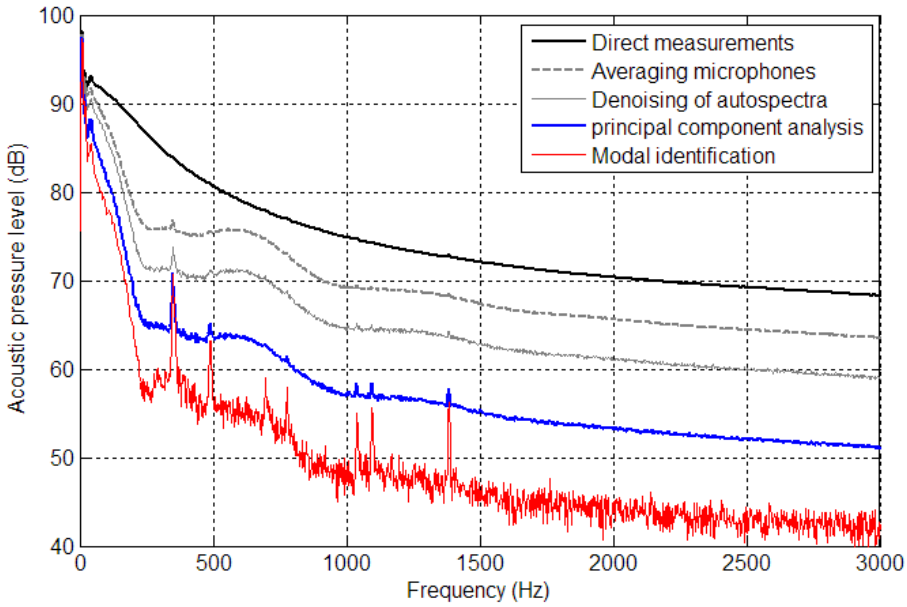


Figure 5: average quadratic pressure spectra. Solid Black: direct measurements. Gray : successive results of steps 1 and 2 (see Fig. 4). Blue: after steps 1, 2 and 3 (PCA, cf. section 5.4), Red: after steps 1,2, 3 and 4 (modal identification).

### 5.5 Comparison between cleaned direct measurements and indirect measurements

The result of the cleaning of direct measurements is shown in Fig. 7 together with indirect measurements. It can be seen that the result of the cleaning procedure has been considerably brought closer to indirect measurements as compared to raw pressures. The peaks that are visible on both results are more energetic for indirect measurements (about 3 to 5dB). In the whole, the observed difference decreases with respect to the frequency. This difference can be explained by the fact that the aerodynamic component remains non negligible in the low and medium frequency, so that the low pass filtering offered by CFAT cannot be considered as an pure extraction of the physical acoustic component. Moreover, above 1500 Hz, some peaks remain not visible on the cleaned direct measurements. It could mean that the cleaning procedure is too strict and removes a part of the acoustic component.

## 6 CONCLUSION

A cleaning procedure for in-flow pressure measurements has been proposed in this work. The result of the procedure is that pressure spectra are lowered by more than 20dB and reach approximately the level that had been previously recovered by indirect measurements. This

result is more than a validation of indirect measurements, it can also be used to future developments where the objective is to extract the physical acoustic part of a turbulent excitation.

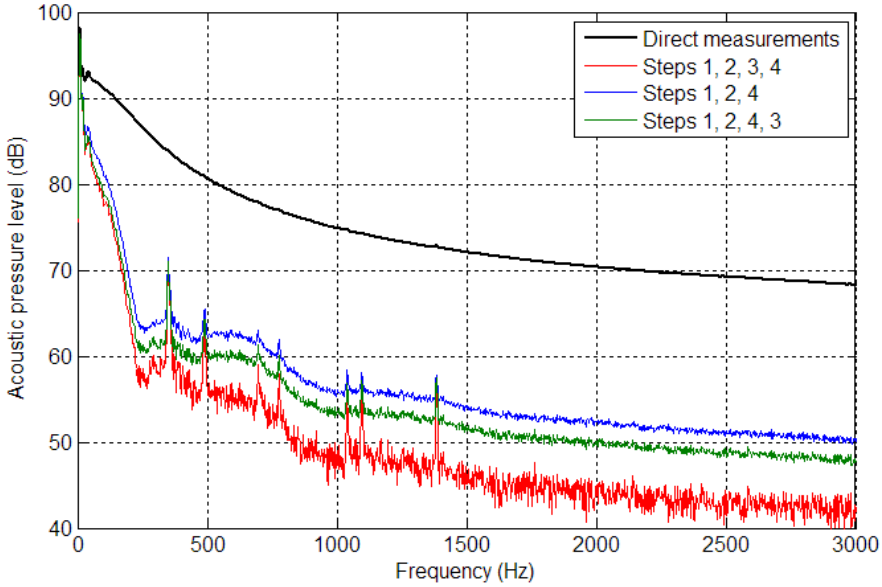


Figure 6: average quadratic pressure spectra. Solid Black: direct measurements. Red: after steps 1,2, 3 and 4 (PCA then modal identification). Blue : steps 1, 2, and 4. Green : steps 1, 2, 4, and 3(modal identification then PCA).

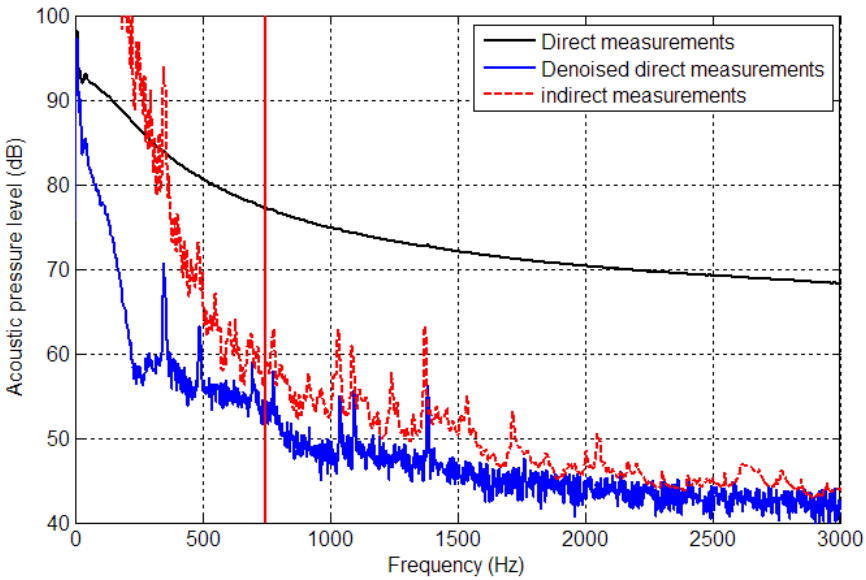


Figure 7: average quadratic pressure spectra. Solid Black: direct measurements. Blue: after cleaning steps 1 to 4. Red: indirect measurements. Thick red vertical line: low frequency limit of the indirect method


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